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Mutual Coherence of Two Coupled Multiline Continuous-Wave HF Lasers

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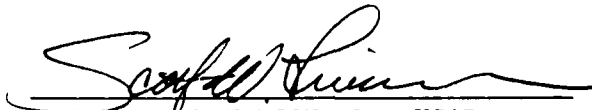
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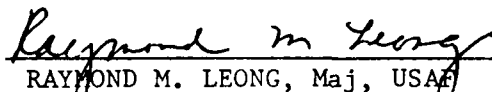
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<p>Two multiline cw HF lasers employing unstable resonators were coupled by injecting 20% of each laser output into the other laser. The mutual coherence of the two output beams was measured by recording the visibility V of the interference fringes generated when the beams are overlapped. Both single-line and multiline interference patterns were observed. The output from the two lasers in the present experiment (20% coupling) was completely coupled, indicating that the achievement of stable coupling is not dependent on careful adjustment of the length of each laser resonator.</p>					
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We consider the coupling of two nominally identical lasers by partial injection of the output from each laser into the other. When steady-state coupling is achieved and the output beams are in phase, the beams can be used to form a phased array.¹ The stability of this system was investigated theoretically by Spencer and Lamb² for a single laser transition. It was found that steady-state coupled operation is achieved when the length of each laser resonator is adjusted so that the empty-cavity frequency is the same for each resonator. A perturbation of one resonator length resulted in reduced stability and ultimately uncoupled operation. Analytic expressions for allowable length perturbations (i.e., lock-in range) are presented by Chow.³

Spencer and Lamb's theory was experimentally confirmed by Palma and Fader¹ with a CO₂ laser. More recently, their theory was generalized to account for arbitrary-length separation between the two coupled lasers.⁴ The conclusion was that, in general, it is not possible to achieve steady-state operation on all potential laser transitions for multiline lasers. However, the effect of mode competition was not considered.

Here, we report initial results from an experimental study that addressed two major technical questions on the performance of two coupled multiline cw HF chemical lasers with unstable resonators: (1) Is it necessary that the two resonators have the same length (to within a fraction of a wavelength) to achieve steady-state coupling? and (2) Is the output coupled for some laser transitions and uncoupled for others?

The test apparatus is diagrammed schematically in Fig. 1. Mirrors M₁-M₂ and M₃-M₄ constitute two nominally identical confocal unstable resonators (length L = 1.5 m, mode diameter = 1 cm, magnification M = 1.4, and equivalent Fresnel number 4.1). They are assembled to enclose a supersonic-diffusion HF gain generator⁵ (maximum gain-length product $g_0 L = 1.8$), so that the two 1-cm-diameter resonator modes are separated vertically by 0.5 cm in the gain region. Coupled or not, the major laser transitions and relative output powers are

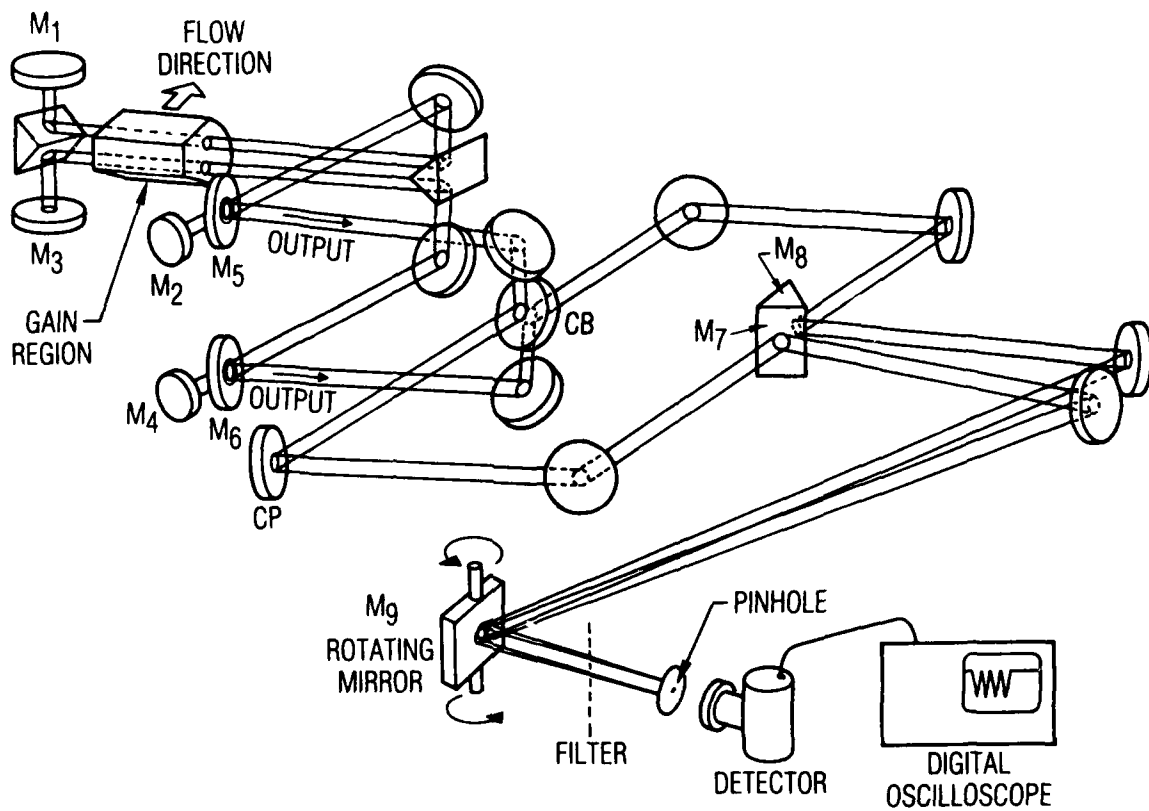


Fig. 1. Schematic diagram of coupled unstable resonators and near-field fringe diagnostics.

$P_1(5):$	12%	$P_2(5):$	14%
$P_1(7):$	2%	$P_2(6):$	36%
$P_1(9):$	1%	$P_2(7):$	29%
$P_2(3):$	0.5%	$P_2(8):$	3%
$P_2(4):$	1.5%		

When coupled, each of the two laser outputs, from hole-scraper mirrors M_5 and M_6 , is directed into the other's resonator through the ZnSe-coupling beam splitter, CB (20% transmission, 80% reflection at one surface and an antireflection coating at the second surface).

The coupling path length between M_5 and M_6 also is approximately 1.5 m. The two laser outputs emerge as the reflection from the coupling beam splitter. A ZnSe-compensating plate, CP, is used in the path of the upper laser output because of the dispersion encountered by the lower laser output, which travels through the coupling beam splitter before being reflected. The laser outputs are directed to mirrors M_7 and M_8 , which become the synthetic aperture for the coupled laser system. These two outputs are made to overlap at an angle of 2 mrad in the near field to produce a pattern of linear interference fringes. Note that fringes appear only if the two outputs are phase related. The fringe pattern is observed on a thermal image screen. It is also translated past a pinhole-detector combination by rotating mirror M_9 and is recorded by an oscilloscope. The oscilloscope trace depicts intensity versus distance along a line perpendicular to the fringes. A filter is placed in front of the pinhole (Fig. 1) to obtain the fringe pattern corresponding to a single laser line.

Fringe visibility V can be deduced from the oscilloscope traces, namely,

$$V = \frac{(I_{\max} - I_{\min})}{(I_{\max} + I_{\min})}$$

where I_{\max} and I_{\min} are the maximum and minimum voltage levels, respectively, above the zero-intensity baseline on the oscilloscope trace. A fringe visibility of 1 corresponds to complete coupling and phase coherence of the two lasers, whereas $V = 0$ implies that the lasers are operating independently.

An enlarged thermal image of the multiline fringe pattern is shown in Fig. 2 for two values of the length of the lower resonator. The appearance of fringes at every cavity length that we tried demonstrates that at least a portion of the output of the two lasers can be coupled without precisely controlling cavity length. The uniformity of the fringes indicates perfect phase coherence of the coupled beams throughout the interaction region.

A typical oscilloscope trace of the upper and lower output beams, and of the multiline fringe pattern, is shown in Fig. 3. In this figure, $V = 0.6$, which implies either incomplete coupling or unequal optical paths for the two beams. To determine whether complete coupling is occurring (i.e., all output power is coupled), it is necessary to either equalize resonator and external optical path length or to measure, separately, the fringe visibility for each line of the multiline interference pattern.

Filters were available that enabled the interference patterns for $P_1(5)$ and $P_2(6)$ to be inspected. A typical fringe pattern for $P_2(6)$ is shown in Fig. 4. For several such traces, the measured visibility was $V = 0.90 \pm 0.02$. After correcting for the finite size of the pinhole relative to the fringe-separation distance, an experimental value of $V = 1.0$ was indicated. Hence, it may be concluded that the laser transition $P_2(6)$ is completely coupled. This result was obtained for both $P_1(5)$ and $P_2(6)$ from a number of tests, which included coarse (millimeter) perturbations of resonator length. Since these two lines may be considered to be typical lasing transitions, it is concluded that, for the 20% coupling, the entire output for both lasers is coupled and the achievement of stable coupling is insensitive to resonator-length equalization. Moreover, the value $V \neq 1$ deduced from Fig. 3 is attributed to unequal resonator and external optical path lengths. The achievement of $V = 1$, needed for a phased array, may require both resonator-length equalization and external-optical-path equalization.

It should be noted that the two outputs of the coupled laser system do not arise from oscillation between mirrors M_1 and M_3 ; the output from either laser ceases when its convex mirror (M_2 or M_4) is blocked. The lack of sensitivity of multiline fringe visibility to resonator length may imply that

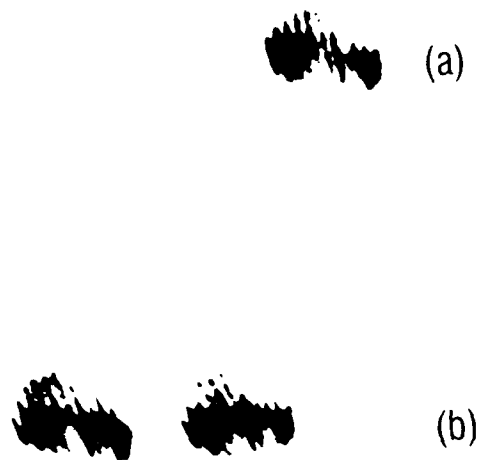


Fig. 2. Expanded thermal image of multilane near-field fringes: (a) lower resonator length $\sim 1.5 \text{ m} + 0.0 \text{ } \mu\text{m}$, (b) lower resonator length $\sim 1.5 \text{ m} + 200 \text{ } \mu\text{m}$.

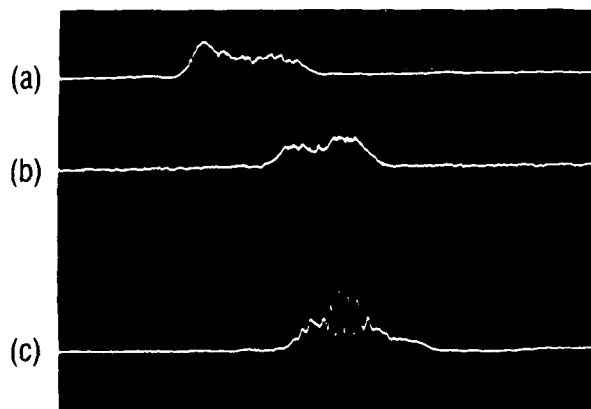


Fig. 3. Oscilloscope traces of multilane near-field scans: (a) lower beam only, (b) upper beam only, and (c) both beams overlapped.

the two lasers oscillate with a mode defined by the sum of the two resonator lengths plus the coupling path length. Longitudinal-mode beat-frequency measurements will be required in order to verify this.⁶

The present results may be explained by Mirels's⁴ theoretical model, about which he notes that stable coupled modes have less round-trip cavity loss than do unstable modes. When these modes compete for the same gain (as occurs in the present inhomogeneously broadened multiline, multilongitudinal-mode HF laser medium), the stable modes will dominate and, in fact, quench the unstable modes. If the coupling is reduced from the present 20%, it is expected that the dominance of the stable, coupled modes will eventually diminish and the system will become more sensitive to resonator-length control. It should also be noted that the theory of Ref. 4 applies strictly to coupled Fabry-Perot resonators and not to unstable resonators such as those in the present experiments. Beam-splitter coupling between confocal unstable resonators implies the presence of converging waves, which effectively amplifies the intensity of the coupling radiation. Theories that incorporate these particular aspects of our experiments may explain our results. Further experiments⁶ have confirmed many of the above conclusions.

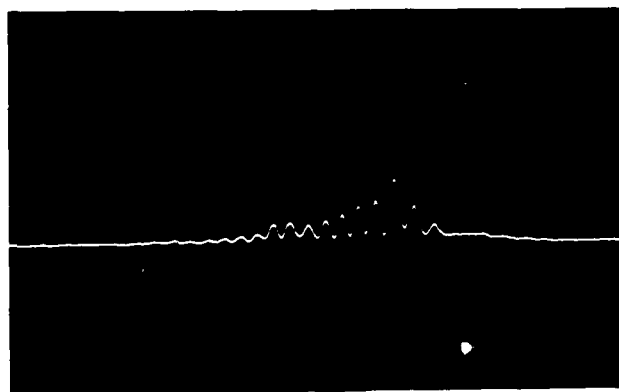


Fig. 4. Oscilloscope trace of $P_2(6)$ single-line fringe pattern.

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